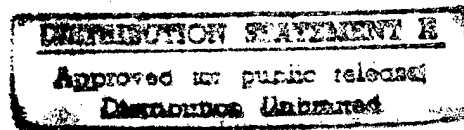


The Nature of the General Factor in Hierarchical Models of the Structure of Cognitive Abilities: Alternative Models Tested on Data from Regular and Experimental Military Enlistment Tests.

Jan-Eric Gustafsson
University of Goteborg

Bengt O. Muthén
Graduate School of Education & Information Studies*

August 13, 1996



19970401 049

bengt/papers/enlist/enlist.tex

Draft

*The research of the first author was supported by a grant from the Bank of Sweden Tercentenary Foundation, and the research of the second author was supported by grant no N0014-93-1-0619 from the U.S. Navy/Office of Naval Research. The authors thank Jane Arabian and Laurie Wise for helpful comments and for facilitating access to Project A data. We acknowledge the expert assistance of Guanghan Liu, Graduate School of Education, UCLA.

INTRODUCTION

Hierarchical models of the structure of cognitive abilities offer theoretical as well as practical advantages (Gustafsson, 1988, 1994a, in press-a; Lohman, 1991). Such models may resolve the conflict between theorists who emphasize one general ability (e. g., Spearman, 1927; Jensen, 1987; Humphreys, 1985), and theorists who emphasize several specialized abilities (e. g., Thurstone, 1938; Guilford, 1967; Gardner, 1985), by allowing for both categories of abilities in the model. The hierarchical approach also offers possibilities for solving prediction problems efficiently and parsimoniously (Gustafsson, 1988, 1989; Muthén, 1994). There are several alternative hierarchical models, however (Gustafsson, 1994a, in press-b).

Carroll (1993) recently presented an elaborate hierarchical model based on reanalyses of a large number of correlation matrices collected throughout the history of research on cognitive abilities. The model has factors of three degrees of generality and is referred to as the "Three-Stratum Model." At the first stratum the model includes at least some 60 narrow factors, many of which correspond to factors previously identified by Thurstone, Guilford and other researchers working in the tradition of multiple factor analysis.

At the second stratum some 10 broad factors are identified, most of which largely correspond to factors identified by Cattell (1963, 1971, 1987), Horn (1980, 1985, 1986, 1988, 1989), Horn and Cattell (1966), and other researchers employing second-order factor analysis. Among the broad factors, two are especially frequent and prominent in the reanalyses, namely Fluid Intelligence (Gf), which is involved in difficult tasks of induction, reasoning, problem solving, and visual perception; and Crystallized

Intelligence (Gc), which is involved in language and reading skills and declarative knowledge in wide areas, and may thus be interpreted as a broad verbal factor. Another frequently identified factor is Broad Visual Perception (Gv) which involves manipulation of figural information, particularly when perception or mental manipulation is complex and difficult. Broad Auditory Perception (Gu) spans a broad range of tasks which reflect the degree to which the individual can cognitively control the perception of auditory stimulus inputs. Broad Retrieval Ability (Gr) is involved in tasks designed to reflect originality and quickness of retrieving symbols. Carroll also identified a second-stratum memory factor (Gy), which spans narrow factors reflecting short-term acquisition of material. The higher-order analyses conducted by Carroll yielded more than one factor involving speed. One factor (Gs) is involved in relatively simple tasks administered under time constraints. Another factor (Gt) dominates various kinds of reaction time tasks. A third factor (General Psychomotor Speed; Gp) is primarily concerned with the speed of finger, hand, and arm movements.

A large number of Carroll's analyses yielded a factor (first-, second- or third-order) with loadings for variables in several different domains which was classified as the stratum III factor General Intelligence (G). The loadings usually are high for complex reasoning tasks and low for psychomotor and speed factors. According to Carroll this suggests that the G-factor involves complex higher-order cognitive processes.

Gustafsson (1984, 1988; 1994b, Gustafsson & Undheim, in press; see also Undheim, 1981; Undheim & Gustafsson, 1987) also has presented a hierarchical model with factors of three degrees of generality. The

structure of this model is therefore quite similar to Carroll's model, even though it is more restricted in scope. Research on this model has shown, however, that the correlation between the second-stratum Gf-factor and the third-stratum G-factor is so close to unity that these factors must be considered identical. Thus, in the Gustafsson model no second-stratum Gf-factor is identified, because the general factor accounts for all the variance in Gf. In this respect this model is similar to the hierarchical model proposed by Vernon (1950), and which may be seen as a development of Spearman's (1904) Two-Factor Model.

The fruitfulness of a general apex factor in hierarchical models has been challenged, however (e. g., Horn, 1989). The major problem is that the nature of the general factor tends to vary from study to study, as a function of which particular tests are included in the test battery. This lack of invariance can be seen in the results reported by Carroll (1993), and even though there is some evidence that the general factor comes close to inductive and non-verbal reasoning abilities, the Carroll series of reanalyses does not bring out such a close equivalence between Fluid Intelligence and General Intelligence as has been found in the Gustafsson studies. One possible explanation for this lack of agreement is that Carroll has relied on exploratory factor analysis, while Gustafsson has used confirmatory factor analytic techniques.

Were it possible to clearly identify the general factor in the hierarchical model as Fluid Intelligence this would solve the problem of non-invariance (Gustafsson, 1994b). It also would bring theoretical advantages when it comes to interpreting the general factor in psychological terms. Thus, among the many attempts to develop an interpretation in process terms of

the nature of the general factor (see Gustafsson & Undheim, in press), a recent approach proposed by Kyllonen and Christal (1989) which relies on the concept of working memory seems to be one of the most interesting and promising. Kyllonen and Christal (1990) have also presented some empirical evidence which supports the idea of a very substantial amount of overlap between measures of working memory capacity and reasoning ability. We may thus formulate the two-linked hypothesis that working memory equals Fluid Intelligence, which in turn equals General Intelligence.

The main purpose of the present paper is to investigate the hypothesis that the general factor in hierarchical models is equivalent to Fluid Intelligence. This will be done on data generated in large scale studies which aim to broaden the range of abilities measured by the Armed Services Vocational Aptitude Battery (ASVAB). The ECAT (Experimental Computer Administered Tasks) project (Wolfe, Alderton, Larson, & Held, 1993) thus has extended the ASVAB with tests measuring reasoning, spatial visualization, psychomotor abilities, and working memory. In the Army Project A (Campbell & Zook, 1991) additional tests have similarly been used to extend the range of abilities covered by the ASVAB. With these extensions it should be possible to identify a factor of Fluid Intelligence, along with several other stratum II and stratum I factors, which makes for a direct investigation of the nature of a stratum III factor of General Intelligence. The fact that the ECAT study involved two tests of working memory capacity also makes it possible to use these data to investigate the hypothesis that Fluid Intelligence equals Working Memory.

METHOD

We will here present results from two modeling studies. One is based on the matrix of correlations of the 10 ASVAB and the 9 ECAT measures estimated for 10,963 subjects and presented as Table B-1 in the Wolfe et al. (1993) report. The other is based on data from the Army Project A, where the 10 ASVAB subtests have been administered to 4,039 subjects along with 12 other cognitive tests (Campbell & Zook, 1991). Table 1 provides a short summary of the subtests involved in the studies. For this analysis a subset of Army Project A tests has been selected to match as closely as possible the subtests in the ECAT battery.

=====

Insert Table 1 about here

=====

Wolfe et al. (1993) factor analyzed the 10 subtests of the ASVAB using an oblique model in an exploratory factor analysis, and identified four primary factors: Technical Knowledge, defined by Auto-Shop Information, Mechanical Comprehension, and Electronics Information; Verbal ability, defined by Word Knowledge and Paragraph Comprehension; Clerical Speed, defined by Numerical Operations and Coding Speed; and Mathematical Ability, with relations to Arithmetic Reasoning and Math Knowledge. An analysis of the correlations among these four factors yielded a general, second-order, factor and according to the orthogonalized hierarchical solution, the subtests Word Knowledge, Arithmetic Reasoning, Math Knowledge and General Science have the highest loadings on the

general factor. This pattern of loadings suggests that the general factor in this analysis is close to the Gc factor.

Wolfe et al. (1993) also reports first- and second-order exploratory factor analyses of the 9 tests of the ECAT battery. The first-order analysis yielded three primary factors: Spatial Ability, with the highest relations to Integrating Details, Assembling Objects, Figural Reasoning and Spatial Orientation; Psychomotor Skill defined by the One and Two Hand Tracking Tests and Target Identification; and Working Memory, defined by Mental Counters and Sequential Memory. The orthogonalized second-order analysis gave evidence of a rather strong general factor with the highest relations to the spatial and figural tests (Assembling Objects, Integrating Details and Figural Reasoning). Thus, the general factor in this analysis seems to come close to the Gv factor.

Wolfe et al. (1993) also reports a hierarchical analysis of the combined ASVAB and ECAT batteries. This analysis replicated the four ASVAB factors, as well as the Spatial and Psychomotor factors of the ECAT battery. There were changes, however, in the general factor and in the Working Memory factor. In the analysis of the combined batteries the highest loadings on the general factor were observed for Arithmetic Reasoning, General Science and Mechanical Comprehension. This general factor is less verbal than the general factor obtained when the ASVAB battery was analyzed separately, and it is less spatial than is the general factor obtained when the ECAT battery was analyzed separately. However, except that the general factor is quite highly related to subtests with mathematical content it is not easily interpreted in psychological terms. Wolfe et al. also observed that the Working Memory factor of the ECAT battery changed into a

broader Non-Verbal Reasoning factor, close to Fluid Intelligence, in the analysis of the combined batteries. They concluded that a major effect of the efforts to broaden the range of abilities measured by ASVAB is the augment the Crystallized Intelligence measures, which seems to dominate the test, with Fluid Intelligence measures.

The exploratory hierarchical factor analyses reported by Wolfe et al. (1993) thus indicate that the ECAT extension provides a basis for identifying at least Gc and Gf as stratum II factors, along with several stratum I factors. However, just as was the case in the Carroll (1993) series of reanalyses, these hierarchical factor solutions provide little support for the hypothesis that the general factor is equivalent with Gf. On the contrary, the results of the three analyses clearly demonstrate that the nature of the general factor is influenced by the composition of the test battery. As has already been suggested this may be due to the less than optimal characteristics of exploratory factor analysis, and we will here take advantage of the increased power and precision of latent variable modeling (see, e.g., Bollen, 1979; Jöreskog & Sörbom, 1979).

Both correlation matrices have been adjusted for selection with the Pearson-Lawley correction before modeling (see, e. g., Dunbar & Linn, 1991). In this correction the ten ASVAB subtests were taken as selection variables and the unselected covariance matrix for the ASVAB subtests was taken to be that of the 650,278 applicants from the fiscal year 1991 given in the Wolfe et al. (1993) report. It should be noted that the conventional chi-square measure of model fit is not strictly applicable here given that a corrected matrix is analyzed. Because of this, more descriptive fit indices will be relied upon. The LISREL VIII program will be used to estimate the models

and it offers several descriptive measures of goodness-of-fit, such as the Root Mean Square Error of Approximation (RMSEA) measure (Browne & Cudeck, 1993), the Goodness of Fit Index (GFI) and Adjusted Goodness of Fit (AGFI) measures, and the Bentler Normed and Non-Normed Fit Indices (NFI and NNFI, respectively; see, Jöreskog & Sörbom, 1993, for a description of all the descriptive fit indices).

In the modeling of both these matrices the same general approach has been adopted, and the hierarchical models have been fitted as orthogonal models with factors of different degrees of generality (so called nested-factor models, see Gustafsson & Balke, 1993). The hypothesized factors have been entered into the model according to degree of generality, starting with a general factor. Then the broad stratum II factors have been entered, and last the narrow stratum III factors have been included. The resulting model thus includes a set of orthogonal factors which are directly related to the observed variables, so the models strongly resemble the orthogonalized solution obtained with a Schmid-Leiman transformation of a higher-order factor model (Schmid & Leiman, 1957).

In addition to a stratum III General factor, there is reason to expect several broad stratum II factors in the present data. Among the ASVAB subtests, in particular, there are several scales which measure verbal competence and knowledge in different fields and which should be indicators of the broad factor Gc. Both in ASVAB and in the experimental batteries there are several tests which involve figural and spatial tasks, which makes it reasonable to hypothesize a General Visualization factor (Cattell, 1987).

It has already been concluded that among the ECAT tests the Gf factor may be identified, which might make it reasonable to try to include a Gf factor in the model as well. However, according to the Gustafsson model the Gf factor is equivalent to the General factor, and because the General factor is already included in the model no residual variance remains to identify a Gf factor. Thus, should it prove necessary to include a Gf factor to achieve model fit, this is empirical evidence against the hypothesis of equivalence of Fluid and General Intelligence.

During the course of modeling, hypotheses have also been formulated about narrow stratum I factors but we will return to those when the models are presented. We would like to emphasize, however, that the modeling approach used here results in fewer stratum I factors than when a higher-order modeling approach is used. This is because the variance represented by the lower-order factors is often absorbed by the more general factors, so when they are already in the model the stratum I factors cannot be identified (see Gustafsson & Balke, 1993). For example, if there is a narrow Working Memory factor, this will cause the model to have poor fit unless the factor is included in the model. However, should the two-linked hypothesis of equivalence between Working Memory, Fluid Intelligence, and General Intelligence be true, we do not expect to find a Working Memory factor in the model.

RESULTS

We first present the model for the battery where the 10 ASVAB subtests have been analyzed together with the 9 ECAT subtests, and then the model

for the ASVAB and Army Project A variables. Finally we present a model for the 10 ASVAB subtests alone.

ASVAB extended with ECAT

For the ASVAB and ECAT variables a six-factor model was arrived at. The RMSEA measure of model fit was .045, which indicates a close fit between model and data; the GFI and AGFI measures were .98 and .96, respectively; and the Bentler NFI and NNFI measures were .98 and .97, respectively. These measures all indicate a very good fit of this model to data.

Table 2 presents the standardized loadings of the 19 observed variables on the 6 orthogonal factors. The first factor is the general factor, with relations to all tests. The highest loadings (.76) are obtained for Mental Counters, Figural Reasoning, and Integrating Details, which all are non-verbal problem solving tasks of kinds known to load highly on Gf. High loadings (.70-.73) also are observed for Arithmetic Reasoning, Assembling Objects and Sequential Memory. These tests also involve non-verbal problem solving. No other factor in the model involves the non-verbal reasoning tests, so there is little doubt that the general factor is interpretable as the dimension of Fluid Intelligence. It may be observed that Gf accounts for a rather modest amount of variance (some 10 % to 40 %) in most of the ASVAB subtests, while Gf is much better represented among the ECAT tests.

=====
Insert Table 2 about here
=====

The second factor has its highest relation (.71) with the Word Knowledge subtest, and the next highest (.55) with Paragraph Comprehension. There also are relations around .40-.50 to other ASVAB subtests such as Auto and Shop Information, Electronics Information, and General Science. This pattern of loadings clearly identifies the factor to be the well-known broad verbal Crystallized Intelligence (Gc) factor. No ECAT test has any relation to Gc, except for a small negative loading on this factor for Mental Counters.

The third factor is also a broad factor with relations to a large number of tests. The highest loading (.70) is observed for Auto and Shop Information, and there are relatively high loadings on Electronics Information and Mechanical Comprehension. This factor is also related to all the spatial and psychomotor tests with coefficients around .25. This factor obviously is a broad spatial factor, close to the Broad Visual Perception factor (Gv) identified by Carroll (1993). The loadings on the mechanically oriented subtests of ASVAB seem too high, however, to allow an interpretation of this factor as an unbiased Gv-factor. Carroll (1993, p. 525) reports that the ASVAB subtests with high loadings on the third factor in several analyses define a Mechanical Knowledge (MK) factor, and it seems that the third factor represents a mixture of this stratum I factor, and the stratum II Gv factor. It will, therefore, be referred to as Gv/MK.

The fourth factor has very high relations to Coding Speed (.66) and Numerical Operations (.71), along with smaller relations to a few other subtests. This factor seems to be dominated by the narrow Perceptual Speed factor (see, e.g., Carroll, 1993), so it will be labeled P.

The fifth factor has the highest relations (.57) to Math Knowledge in ASVAB and there are lower relations to Arithmetic Reasoning and some other ASVAB subtests. This factor obviously is related to subtests which involve mathematical tasks and it will be referred to as the Math factor (cf. the A3 and KM factors in Carroll, 1993, p. 523).

The sixth factor, finally, is highly related to the three psychomotor tasks of the ECAT battery. Carroll (1993) found a second-order speed factor involved in tasks concerned with the speed of finger, hand and arm movements, which was interpreted as General Psychomotor Speed (Gp). It seems quite reasonable to interpret the sixth factor along similar lines, so it will be referred to as Gp.

Before leaving the model for the ECAT tests it should also be pointed out that the model includes a rather substantial correlation between the errors (i.e., specific components) of Assembling Objects and Target Identification. This correlation, which is positive, may perhaps be interpreted as representing a narrow spatial factor, which may be due to the fact that the tasks in both these tests require rotation of spatial objects, among other things. The model also includes a smaller, negative, correlation between the errors of Arithmetic Reasoning and Assembling Objects, as well as a small positive correlation between the errors of Mental Counters and Sequential Memory. The latter correlation seems to represent a weak residual

Working Memory factor, which indicates that the two-linked hypothesis is not fully supported. Thus, while Fluid Intelligence seems to collapse completely into the General factor, it does seem that there is a small Working Memory residual left in these tests. It should be stressed, however, that this residual is small, and that the loadings of the Working Memory tests on Gf are very large.

ASVAB and Army Project A tests

We now turn to the model for ASVAB and the Army Project A. For the 10 ASVAB and 12 enhancement tests a model with 6 factors was also arrived at. The descriptive measures indicate a very good fit: RMSEA is .038, which is even better than what was obtained for the model for ASVAB and ECAT; GFI and AGFI are .98 and .96, respectively; and NFI and NNFI are .98 and .97, respectively. These measures all indicate a very good fit of the model to data.

Table 3 presents the standardized loadings of the observed variables on the six latent variables. The first factor is, of course, a general factor and it may be observed that for the variables that are common between this model and the previous model the loadings are highly similar. The highest loading (.77) is observed for the Figural Reasoning test and other high loadings are obtained with tests which require non-verbal problem solving (no working memory tests were included in this analysis). For most of the ASVAB subtests the size of loadings are very close to those of the ECAT model, even though the Arithmetic Reasoning loading is somewhat lower in the

Army Project A model. There is little doubt, however, that the general factor may be interpreted as the Gf factor here also.

=====

Insert Table 3 about here

=====

The second factor has its highest relations with Word Knowledge and Paragraph Comprehension, and again the pattern of loadings is strikingly similar to the second factor of the ECAT model. This factor may thus be labeled Gc in this model too.

The third factor has, if possible, an even greater degree of similarity to the third factor (Gv/MK) in the ECAT model. Thus, for the common subtests the loadings agree to within .01-.03, and the spatial subtests which are unique to the Army data yield a pattern of loadings which supports the interpretation of this factor as a Gv/MK factor. The fourth factor displays a pattern of loadings which again is virtually identical to that observed in the ASVAB+ECAT model, so here too we label this factor P. The fifth factor is the Math factor, with loadings that agree very well with those obtained in the ECAT model.

The sixth factor, finally, is related to the psychomotor variables. In the present model this factor is broader, however, and the loadings of the subtests are lower. The interpretation of this factor as a General Psychomotor Speed factor (Gp) seems warranted here too, however.

The models for the two sets of variables thus result in six factors which are virtually identically defined. However, in the model including the Project A variables it proved necessary to include a few correlated errors to achieve model fit. This was primarily because in some cases more than one score was derived from the same test (i.e., the Memory Search Test and the Target Identification Test), and that there is a high degree of similarity between certain tasks (i.e., Target Tracking Test 1 and Target Tracking Test 2). There also were correlations among some variables which may be expression of a broad speediness factor (Memory Search Test, Time and Target Identification, Time; Memory Search Test, Time and Target Identification, Hits).

ASVAB only

From a practical point of view it is quite interesting to investigate the properties of a hierarchical model fitted to the 10 subtests of ASVAB alone. It is not possible to identify all six factors of the two previous models from the covariances among the ASVAB subtests. Thus, there are no psychomotor tests in the ASVAB, so the Gp factor may not be identified. An attempt has been made, however, to fit a model with the other five factors. In order to achieve convergence it proved necessary to make the model somewhat more restricted in the sense that the P- and Math-factors were allowed relations to somewhat fewer ASVAB tests than in the other two models. The model fits very well, however (RMSEA=0.04, GFI=1.00, AGFI=0.98, NFI=1.00, NNFI=0.99), and as may be seen from the estimates presented in Table 4, the general structure of this model is the same as for the other models.

=====

Insert Table 4 about here

=====

It is an interesting question whether the general factor of this model may also be interpreted as Gf. However, the loadings of most of the ASVAB subtests on the general factor are lower in this model than in the other two models. The mathematical subtests have higher loadings on the general factor in the model for ASVAB only than when other subtests are invoked as well. Thus, the invariance does not seem to apply here, and the general factor should not be interpreted as Gf. The reason for this is, of course, the lack of non-verbal reasoning tests in ASVAB. This makes it impossible to estimate the Gf factor properly when only ASVAB tests are relied upon. For the other factors the general pattern of loadings seems to support the same interpretations of factors as for the corresponding factors in the other models. However, there are some differences in size of loadings which makes it an open question what degree of non-invariance is achieved for these factors.

DISCUSSION AND CONCLUSIONS

In the two models fitted to the ASVAB extended with subtests measuring non-verbal reasoning and spatial abilities, the general factor of the hierarchical model is clearly interpreted as the Gf-factor. There is no other inductive reasoning, or non-verbal reasoning factor in the model so it may be concluded that the empirical results support the equivalence of Fluid Intelligence and General Intelligence. It may also be noted that the

estimated loadings are very similar over the two models for identical variables, which does demonstrate a substantial degree of invariance in spite of the fact that only a subset of the ECAT and Army Project A tests are identical.

When a hierarchical model is estimated for ASVAB alone the general factor is not identical with Gf, however. To be able to establish a hierarchical model for ASVAB that is invariant it thus seems that the battery must be enhanced with one or more non-verbal reasoning tests. It is an interesting task for future research to determine how many such tests are needed to achieve an invariant model.

Another hypothesis investigated was that a factor defined by measures of working memory capacity is identical with Fluid Intelligence. It is indeed the case that the ECAT working memory tests have as high loadings on Gf as does the Figural Reasoning test and this supports the hypothesis. In the model for the ASVAB and the ECAT tests it proved possible, however, to estimate a covariance between the specific components of the two working memory tests. This suggests that there may be a weak working memory factor over and above Gf. To investigate the properties of such a factor it would be essential, however, to have at least one more working memory test, because an unconstrained working memory factor cannot be identified within a hierarchical model unless there are at least three indicators of the factor.

The other factors included in the six-factor models seem to correspond very well to broad and narrow dimensions of ability established in previous research. One exception, however, is the factor which has here been

labeled Gv/MK, which is hypothesized to be a mixture between a stratum I (MK) and a stratum II (Gv) factor. In future research is essential that the different factors in the spatial-mechanical-visualization domain are separated, which should be possible if a wider range of tests from this domain are included in the model.

The patterns of loadings observed for subtests in the ASVAB show that the subtests are factorially complex. Thus, most of the subtests have substantial loadings on three or four latent variables. Given the limited number of subtests in the ASVAB, this implies that it is difficult to achieve a clear separation of the different latent variables. However, if the hierarchical model is to be used for purposes of selection and classification it is necessary to be able to make reliable and valid estimates of the latent variables. Future research should thus investigate which combination of tests and items would be optimal for estimating factor scores on the six latent variables identified here. It also would be worthwhile to consider if other dimensions from the hierarchical model of cognitive abilities should be measured for purposes of predicting different criteria.

REFERENCES

- Browne, M. W., & Cudeck, R. (1993). Alternative ways of assessing model fit. In K. A. Bollen & J. S. Long (Eds.) Testing structural equation models. San Francisco: Sage.
- Bollen, K. A. (1989). Structural equations with latent variables. New York: Wiley.
- Campbell, J. P., & Zook, L. M. (Eds). Improving the selection, classification, and utilization of Army enlisted personnel: Final report on Project A. Research Report 1597, U. S. Army Research Institute for the Behavioral and Social Sciences.
- Carroll, J. B. (1993). Human cognitive abilities. Cambridge: Cambridge University Press.
- Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. Journal of Educational Psychology, 54, 1-22.
- Cattell, R. B. (1971). Abilities: Their structure, growth, and action. Boston: Houghton Mifflin.
- Cattell, R. B. (1987). Intelligence: Its structure, growth and action. New York: North-Holland.
- Dunbar, S. B., & Linn, R. L. (1991). Range restriction adjustments in the prediction of military performance. In A. K. Wigdor & B. F. Green (eds.) Performance assessment for the workplace (pp. 127-157). Washington, D. C.: National Academy Press.
- Gardner, H. (1985). Frames of mind: The theory of multiple intelligences. New York: Basic Books.
- Guilford, J. P. (1967). The nature of human intelligence. New York: McGraw-Hill.

Gustafsson, J.-E. (1984). A unifying model for the structure of intellectual abilities. Intelligence, 8, 179-203.

Gustafsson, J.-E. (1988). Hierarchical models of individual differences in cognitive abilities. In R. J. Sternberg, Advances in the psychology of human intelligence. Vol. 4, (pp. 35-71). Hillsdale, New Jersey: Lawrence Erlbaum Associates, Inc.

Gustafsson, J. E. (1989). Broad and narrow abilities in research on learning and instruction. In R. Kanfer, P. L. Ackerman, & R. Cudeck (Eds.), Abilities, motivation, and methodology. The Minnesota symposium on learning and individual differences, (pp. 203-237). Hillsdale, NJ: Erlbaum.

Gustafsson, J.-E. (1994a). Models of intelligence. In T. Husén & N. Postlethwaite (Eds.) International Encyclopedia of Education (2nd ed). Oxford: Pergamon Press.

Gustafsson, J.-E. (1994b). Hierarchical models of intelligence and educational achievement. In A. Demetriou & A. Efklides (Eds.) Intelligence, mind and reasoning: Structure and development, Elsevier.

Gustafsson, J.-E. (in press-a). General intelligence. In R. J. Sternberg (Ed.) Encyclopedia of Human Intelligence. New York: Macmillan.

Gustafsson, J.-E. (in press-b). Hierarchical theories. In R. J. Sternberg (Ed.) Encyclopedia of Human Intelligence. New York: Macmillan.

Gustafsson, J. E., & Balke, G. (1993). General and specific abilities as predictors of school achievement. Multivariate Behavioral Research, 28, 407-434

Gustafsson, J. E., & Undheim, J. O. (in press). Individual differences in cognitive functions. In D. Berliner, & R. Calfee (Eds.), The Handbook of Research in Educational Psychology, New York: Macmillan.

Horn, J. L. (1980). Concepts of intellect in relation to learning and adult development. Intelligence, 4, 285-317.

- Horn, J. L. (1985). Remodeling old models of intelligence. In B.B. Wolman (Ed), Handbook of intelligence. Theories, measurements, and applications, (pp. 267-300). New York: John Wiley & Sons.
- Horn, J. L. (1986). Intellectual ability concepts. In R. J. Sternberg (Ed.), Advances in the psychology of human intelligence: Vol 3, (pp. 35-77). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Horn, J. L. (1989). Models of intelligence. In R. L. Linn (Ed.), Intelligence. Measurement, theory and public policy, (pp. 29-73). Urbana: University of Illinois Press.
- Horn, J. L., & Cattell, R. B. (1966). Refinement and test of the theory of fluid and crystallized intelligence. Journal of Educational Psychology, 57, 253-270.
- Humphreys, L. G. (1985). General intelligence. An integration of factor, test and simplex theory. In B.B. Wolman (Ed), Handbook of intelligence. Theories, measurements, and applications, (pp. 201-224). New York: John Wiley & Sons.
- Jöreskog, K. G., & Sörbom, D. (1979). Advances in factor analysis and structural equation models. Cambridge, MA: Abt Books.
- Jöreskog, K. G., & Sörbom, D. (1993). LISREL 8: Structural equation modeling with the SIMPLIS command language. Chicago: Scientific Software International.
- Kyllonen, P. C., & Christal, R. E. (1989). Cognitive modeling of learning abilities: A status report of LAMP project. In R. Dillon, & J. W. Pellegrino (Eds.), Testing: Theoretical and applied issues, New York: Freeman.
- Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability is (little more than) working-memory capacity?!. Intelligence, 14(4), 389-433.

- Muthén, B. (1994). A note on predictive validity from a latent variable perspective. Technical Report. UCLA.
- Schmid, J., & Leiman, J. M. (1957). The development of hierarchical factor solutions. Psychometrika, 22, 53-61.
- Spearman, C. (1904). "General intelligence," objectively determined and measured. American Journal of Psychology, 15, 201-293.
- Spearman, C. (1927). The abilities of man. London: MacMillan.
- Thurstone, L. L. (1938). Primary mental abilities. Psychometric Monographs, No. 1.
- Undheim, J. O. (1981). On intelligence II: A neo-Spearman model to replace Cattell's theory of fluid and crystallized intelligence. Scandinavian Journal of Psychology, 22, 181-187.
- Undheim, J. O., & Gustafsson, J. E. (1987). The hierarchical organization of cognitive abilities: Restoring general intelligence through the use of linear structural relations (LISREL). Multivariate Behavioral Research, 22, 149-171.
- Vernon, P. E. (1950). The structure of human abilities. London: Methuen.
- Wolfe, J. H., Alderton, D. L, Larson, G. E., & Held, J. D. (1993). Incremental validity of enhanced computer administered testing (ECAT). Manuscript. Navy Personnel Research and Development Center, San Diego, California.

Table 1. Summary of tests involved in the modeling studies.

Subtest	Description
<u>ASVAB subtests:</u>	
General Science	Knowledge test of physical and biological sciences, 25 items.
Arithmetic Reasoning	Arithmetic word problems, 30 items.
Word Knowledge	Vocabulary test using synonyms or words embedded in sentences, 35 items.
Paragraph Comprehension	Reading comprehension, 15 items
Numerical Operations	Addition, subtraction, multiplication and division using one and two digit numbers, 50 speeded items.
Coding Speed	Recognition of number strings arbitrarily associated with words in a table, 84 speeded items.
Auto and Shop Information	Knowledge test of automobiles, shop practices, tools, and tool use, 25 items.
Math Knowledge	Algebra, geometry, fractions, decimals and exponents, 25 items.
Mechanical Comprehension	Mechanical and physical principles, 25 items.
Electronics Information	Knowledge test about electronics, radio, and electrical principles and information, 20 items.
<u>ECAT subtests:</u>	
Assembling Objects	Spatial tasks involving rotation and combination of parts of an object, 32 items.
Mental Counters	Working memory test using figural content
Figural Reasoning	Figural series extrapolation, 35 items.
Integrating Details	Spatial visualization tasks of the form board type, 40 items.
Sequential Memory	Working memory test using numerical content, 35 items.
Spatial Orientation	Spatial apperception and rotation, 24 items.
One-Hand Tracking	Single-limb psychomotor tracking, 18 items.
Two-Hand Tracking	Multi-limb psychomotor tracking, 18 items.
Target Identification	Figural perceptual speed, 36 speeded items.
<u>Army Project A subtests:</u>	
Assembling Objects	Same as ECAT Assembling Objects
Figural Reasoning	Same as ECAT Figural Reasoning
Maze Test	Mazes with four entrance and three exit points, 24 items.
Object Rotation Test	Rotation in two and three dimensions of simple figures, 90 speeded items.
Memory Search Test, Time	A stimulus set with one to five letters is shown briefly, and the task is to decide if a probe item was in the set or not.
Memory Search Test, Hits	Mean hit rate of the Memory Search Test.
Orientation Test	Mental rotation under constraints of directional orientation, 24 items.
Map Test	Movement in given compass directions on a map.
Target Tracking Test 1	One-hand psychomotor tracking.
Target Tracking Test 2	Two-hand psychomotor tracking.
Target Identification, Time	Figural perceptual speed (time), similar too but not identical with the ECAT test.
Target Identification, Hits	Mean hit rate of the Target Identification test.

Table 2. Standardized Factor Loadings of the Tests on the Six Latent Variables Identified in the Model for the ASVAB and ECAT Batteries.

Test	Gf	Gc	Gv/MK	P	Math	Gp
General Science	0.59	0.52	0.25	-. -	0.17	-. -
Arithmetic Reasoning	0.73	0.21	0.17	0.17	0.27	-. -
Word Knowledge	0.58	0.71	-. -	0.12	-. -	-. -
Paragraph Comprehension	0.54	0.55	-. -	0.24	-. -	-. -
Numerical Operations	0.41	-. -	-. -	0.71	0.16	-. -
Coding Speed	0.41	-. -	-. -	0.66	-. -	-. -
Auto and Shop Information	0.28	0.38	0.70	-. -	-. -	-. -
Math Knowledge	0.68	0.12	-. -	0.18	0.57	-. -
Mechanical Comprehension	0.60	0.28	0.49	-. -	0.14	-. -
Electronics Information	0.38	0.44	0.55	-. -	0.14	-. -
Assembling Objects	0.72	-. -	0.29	-. -	-. -	-. -
Mental Counters	0.76	-0.13	-. -	-. -	-. -	-. -
Figural Reasoning	0.76	-. -	0.11	-. -	-. -	-. -
Integrating Details	0.76	-. -	0.26	-. -	-. -	-. -
Sequential Memory	0.70	-. -	-. -	-. -	-. -	-. -
Spatial Orientation	0.68	-. -	0.26	-. -	-. -	-. -
One-Hand Tracking	-0.44	-. -	-0.21	-. -	-. -	0.68
Two-Hand Tracking	-0.47	-. -	-0.27	-. -	-. -	0.72
Target Identification	-0.38	-. -	-0.16	-. -	-. -	0.23

Table 3. Standardized Factor Loadings of the Tests on the Six Latent Variables Identified in the Model for the ASVAB and Project A Batteries.

Subtest	Gf	Gc	Gv/MK	P	Math	Gp
General Science	0.56	0.55	0.24	-.	0.17	-.
Arithmetic Reasoning	0.67	0.27	0.20	0.18	0.31	-.
Word Knowledge	0.57	0.72	-.	0.12	-.	-.
Paragraph Comprehension	0.56	0.54	-.	0.22	-.	-.
Numerical Operations	0.42	-.	-.	0.72	0.16	-.
Coding Speed	0.44	-.	-.	0.63	-.	-.
Auto and Shop Information	0.20	0.45	0.70	-.	-.	-.
Math Knowledge	0.68	0.13	-.	0.16	0.57	0.08
Mechanical Comprehension	0.57	0.32	0.52	-.	0.13	-0.05
Electronics Information	0.31	0.51	0.53	-.	0.15	-.
Assembling Objects	0.68	-.	0.27	-.	-.	-.
Figural Reasoning	0.77	-.	0.17	-.	-.	-.
Maze Test	0.56	-.	0.29	-.	-.	-0.35
Object Rotation Test	0.48	-.	0.31	-.	-.	-0.22
Memory Search Test, Time	-0.17	0.10	-0.06	-.	-.	-.
Memory Search Test, Hits	0.37	-.	-.	-.	-.	-.
Orientation Test	0.63	-.	0.28	-.	-.	-.
Map Test	0.72	0.13	0.29	-.	0.11	-.
Target Tracking Test 1	-0.38	-.	-0.35	-.	-.	0.30
Target Tracking Test 2	-0.40	-.	-0.36	-.	-.	0.30
Target Identification, Time	-0.40	-.	-0.27	-.	-.	0.41
Target Identification, Hits	0.23	-.	-.	-.	-.	-.

Table 4. Standardized Factor Loadings of the 10 ASVAB subtests on the Five Latent Variables Identified in the Model for ASVAB only.

	Gen	Gc	Gv/MK	P	Math
General Science	0.50	0.63	0.24	-.	-.
Arithmetic Reasoning	0.68	0.37	0.20	0.11	0.23
Word Knowledge	0.38	0.83	-.	0.21	-.
Paragraph Comprehension	0.45	0.61	-.	0.26	-.
Numerical Operations	0.53	-.	-.	0.59	0.21
Coding Speed	0.48	-.	-.	0.65	-.
Auto and Shop Information	0.11	0.47	0.72	-.	-.
Math Knowledge	0.84	0.21	-.	-.	0.25
Mechanical Comprehension	0.48	0.44	0.49	-.	-.
Electronics Information	0.31	0.51	0.54	-.	-.